Study of ice cloud microphysics and in-cloud vertical air motion by cloud radar with Doppler function

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論 文 内 容 要 旨

Importance of ice clouds in the climate system is well addressed in recent years [Stephens et al., 1990]. Over decades, many efforts using satellites with passive instruments have been made and they provided effective knowledge on the role of clouds on the radiation budget and water cycles [e.g., Rossow and Schiffer, 1999].

Yet, further quantitative understanding seems to require information on the vertical structure of clouds on both macro-scale and microphysical properties. Among clouds, information of the vertical distribution of ice clouds has been much less, and the variation in particle habits also produces another difficulty to assess the role of these clouds in climate. Since the duration time of ice clouds depend much on the cloud microphysics and their interaction between the surrounding atmospheres, these results address the necessity of the knowledge of vertical profile of ice cloud microphysics, i.e., effective radius reff, shape, and ice water content IWC. For such requirement, much attention has been paid on active sensors such as lidar and radar. Especially, 95-GHz cloud radar with Doppler functions can detect the full vertical profiles of thick ice clouds without severe attenuation and the Doppler velocity VD is beginning to be recognized as a power tool for particle sizing and thus reducing the uncertainty in the microphysics retrieval performed by radar reflectivity Ze alone. Despite the high potential of Doppler cloud radar, many factors such as particle shape, density, and air motion account for its interpretation, which prevents its use to realize high performances in ice microphysical retrieval. Therefore the development of a reliable tool for the interpretation of the relatively new Doppler cloud radar signals is highly demanded and discussed in this thesis with the following contents.

In Chapter 2, to assess the controlling factors for the radar observables in ice cloud studies, the effect of density, shape, and orientation on radar reflectivity factor (Ze) and linear depolarization ratio (LDR) at 95 GHz are investigated by using the discrete dipole approximation (DDA). We consider hexagonal plate, hollow hexagonal column, and hollow bullet rosette in horizontal (2-D) or three-dimensional (3-D) random orientation. We first validate a widely used method to take into account the density and shape effects by the combinational use of Mie theory with the Maxwell-Garnett mixing rule (the MG-Mie method). It is found that the MG-Mie method underestimates Ze and its applicability is limited to sizes smaller than 40 μm. On the basis of the DDA, it is possible to separately treat density, aspect ratio, orientation, and shape. Effect of density turns out to be minor. Orientation and shape are the major controlling factors for Ze especially at reff $>$ 100 μm and LDR except for very large sizes where the effect of orientation in LDR diminishes. Comparison between the DDA results and the analytical solution for 3-D Rayleigh spheroids shows' that LDR in the small size range is characterized by the target boundary and aspect ratio. In the large size range, LDR reveals features of a single target element; for example, LDR of bullet rosette is similar to that of a single branch of the particle. Combinational use of Ze and LDR is effective in microphysics retrieval for LDR $<$ -23 dB. For LDR $>$ -23 dB, additional information such as VD is required.

By incorporating the non-sphericity effects into look up tables, we introduce a combined 95-GHz radar multi-parameter (Ze, VD, and/or LDR) and lidar backscatter coefficient βbk algorithm for the simultaneous retrieval of ice cloud microphysics and in-cloud vertical air motion Vair within a single radar volume in Chapter 3. Unlike earlier methods, our new approach is not limited to a specific temporal or spatial scale of Vair, which makes it applicable to the interaction between cloud dynamics and ice cloud microphysics on various scales. Full one-to-one validation of the retrieved Vair was performed, for the first time, by collocated VHF Doppler radar measurement (Equatorial Atmospheric Radar) every 3 min for a cloud observed on 14 November 2005, at Kototabang, West Sumatra, Indonesia. The spatial structure of the retrieved up-/downward Vair in cloud agreed closely with direct measurements, with an average difference of -0.009 $\pm$ 0.119 ms-1. The frequency distributions for the retrieved and measured Vair also agreed closely, with peaks of similar width observed around 0 ms-1. A large improvement in the microphysical retrieval was achieved due to the accurate estimation of the Ze-weighted particle fall velocity Vtz from VD. The correlation coefficient between ice water content retrieved with the estimated Vair and that retrieved with the Vair measured by the EAR improved to 0.70 from values as low as 0.28 without the Vair retrieval. By participating the ice microphysical retrieval validation campaign, the accuracy of the microphysics estimate by the algorithm has been intensively tested against in situ datasets of various types of ice particles [Heymsfield et al., 2008]. The accuracy of the method was 95 $\pm$ 15% on average for IWC and was optimized to provide microphysics retrieval results with the smallest standard deviation from observations compared to other algorithms.

In Chapter 4, the developed algorithm was applied to the radar/lidar data collected from the Research Vessel Mirai of JAMSTEC (Japan Agency for Marine-earth Science and TECnology) over the Tropical Western Pacific in late 2001 to characterize the ice cloud properties of the region in conjunction with the weather regime classification of the ISCCP. The weather regimes over the TWP were classified into 6 categories by the cloud cluster analysis based on the ISCCP D1 data. The weather regime was mostly determined to be convectively active (71% of the observation period). Cloud fraction of ice clouds CFice for 40-minute observed by radar was larger when the region was determined to be more convectively active by the ISCCP category. Generally, the vertical variation of ice cloud reff and IWC had good positive correlation with that of the Radiosonde relative humidify and the Vair intensity, and the IWC was the largest for the most convectively active regime. The observed cloud properties in each regime were compared to those of the simulated clouds in GCM by using the radar-lidar simulators. It was found that for convective active regimes, GCM needs to reduce/increase the frequency of cloud occurrence at altitude 〈11km/〉 11km and reduce CFice for a cloud at all height. For convectively inactive regimes, both cloud occurrence and CFice were too large in GCM. The GCM generally overestimated and underestimated reff and grid-mean IWC (IWCgm) for all weather regimes, respectively. The peak of the frequency distribution of the simulated IWCgm was similar to observation at altitude 〈11 km, while it was under-predicted to about an order at altitude〉 11 km.

Among various factors that are considered to be essential for cloud generation and maintenance in each ISCCP weather regime, the dependence of cloud occurrence on both cloud-scale and large-scale vertical velocity is focused in Chapter 5. Analyses of the in-cloud vertical velocity statistics showed that the derived in-cloud vertical velocities could be used to represent those of the large-scale for cloudy regions when they were up-scaled by time averaging. In Chapter 5, the large-scale vertical motion for all sky deduced form the NCEP-NCAR Reanalysis and that for the cloud regions obtained by radar/lidar were characterized by the radar/lidar observed cloud fraction and by the weather regimes to examine their interrelations. Both velocity observations showed that large-scale vertical velocity has similar trends among the weather regimes associated with similar cloud systems, i.e., generally large-scale ascent when CFice is small, and descent when CFice is large especially for pressure>300 hPa. For the same cloud systems, clouds in convectively inactive weather regimes were more embedded in large-scale descent compared to those in convectively active weather regimes. The results indicated that the large-scale vertical wind could have influence on the radar / lidar observed cloud occurrence and its maintenance. Discrepancy in the large-scale vertical velocity signs between that obtained for all sky and for the cloud regions was found in the convectively active regimes.

For future study, application of the developed retrieval method to cloud radar observations from satellite platforms such as CloudSat (National Aeronautics and Space Administration [NASA] / Earth System Science Pathfinder Program [ESSP]) and EarthCare mission (European Space Agency [ESA] / Japan Aerospace

Exploration Agency [JAXA]) are expected to provide unique and valuable information to grasp the dynamical and microphysical view of ice cloud structures over the globe.

論文審査の結果の要旨

佐藤可織は、氷粒子で構成された雲の生成と消滅のメカニズムを研究することを目的とし研究を開始しました。まず 95 GHz 帯の雲レーダに対する様々な形状の氷粒子の散乱特性を理論計算によって求めました。従来、氷粒子は成長に伴って、非球形性が増すことで密度低下が起き、そのレーダ後方散乱特性に対する影響は非常に大きいとされてきました。この結果は、平均誘電率理論 Maxwell-Garnett 理論と、Mie 理論を組み合わせた、MG-Mie 理論に基づいていましたが、その信頼性には疑問がありました。そこで Discrete Dipole Approximation (DDA) 法を用い正確な計算を実施しました。その結果、MG-Mie 理論はその適用可能な範囲が粒子サイズで 40 ミクロン以下の小さい粒子のみで、それより大きくなると 1 桁以上間違った結果を与えること、形状による効果が支配的であることを示しました。

次に、95 GHz 雲レーダのドップラー機能とライダを組み合わせたアルゴリズムを開発しました。従来ドップラーの解析には、粒子の落下速度だけでなく、鉛直流の影響があるため解析が困難でした。本研究では氷粒子の微物理特性と雲内の鉛直流を同時に解析できるという画期的なものです。雲レーダと赤道大気レーダ（EAR）の同時解析データも利用し、鉛直流が極めて良い精度で得られると示すことができました。またアメリカのグループの提案するアルゴリズム検証実験にも参加し、ドップラー機能を使うもののなかで、最高の成績を収めることも示しました。このアルゴリズムは 2013 年に日欧共同で打ち上げ予定である Earth CARE ミッションでの採用が期待されます。さらに、観測船みらいの雲レーダとライダの同時観測結果から、熱帯における氷微物理特性と鉛直流の特性を求め、大気大循環モデル (GCM) の雲再現性を検証しました。この結果、氷水量は、11 ｋｍより上層では 1 桁モデルが過大評価し、それより下の高度では 1 桁程度過小評価しているとの結論を得ることができました。このことはモデル開発における今後の大きな指針を与えるものとして評価できます。

以上の成果は、自立して研究活動を行うに必要な高度の研究能力と学識を有することを示しています。したがって，佐藤可織提出の博士論文は，博士（理学）の学位論文として合格と認めます。